Report No. TE 4067-113-67

THIRD QUARTERLY REPORT

HEAT PIPE THERMIONIC CONVERTER DEVELOPMENT

Contract No. 951465

11 January to 30 April 1967

Prepared for

The Jet Propulsion Laboratory
Pasadena, California

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THIRD QUARTERLY REPORT
HEAT PIPE THERMIONIC CONVERTER DEVELOPMENT

1. Introduction

This document constitutes the Third Quarterly Report of the work being performed under Thermo Electron's Contract No. 951465 with the Jet Propulsion Laboratory.

This report covers progress for the period 11 January to 30 April 1967. During this period, both models T/E-1 and T/E-2 have been fabricated and tested.

2. Fabrication of T/E-1-D

As mentioned in the Second Quarterly Report, the fabrication of the model T/E-1-D had proceeded to the point where a leak had been found between the radiator tube and the collector. This leak was repaired by a second pass in the beam welder.

No further problems were encountered in the fabrication of this model except that it was discovered after assembly that the inner capillary mesh screen, part No. 18, which is wrapped around the inner heat pipe tube, had been omitted accidentally. Figure 1 reproduces the layout of the heat pipe model and shows this part. Another minor difficulty which may be of interest was encountered when making the final heat pipe weld between the end cap, part No. 21, and the inner heat pipe tube, part No. 14. The difficulty is that the cesium reservoir tube, part No. 13, never lies perfectly concentric with the inner heat pipe tube, part No. 14, and as a result it tends to rest at some point around the circumference of tube 14 right next to the region where a weld must be made between the end of tube 14 and the end cap 21. There is then the danger that, during the welding operation, the cesium reservoir tube will be welded to the inner heat pipe tube in the region of the weld. This problem was avoided by a coiled 5-mil-diameter tungsten wire around tube 13, slipped between tubes 13 and 14 in order to ensure concentricity. The weld could then be performed with no further difficulty, but the wire which had been inserted could not be removed, and as a result parts 22 (two wraps of tantalum shielding around the cesium reservoir tube) could no longer be inserted in order to shield the cesium reservoir tube from the radiation from the inner heat pipe tubulation.

Since no experimental evidence was yet available that these shields were necessary for proper operation of the cesium reservoir, they were omitted from the assembly of T/E-1-D. Tests have shown that these shields may be unnecessary for proper operation of the cesium reservoir.

3. Sodium Charge of T/E-1-D

To charge the model T/E-1-D with sodium, a copper manifold containing the sodium capsule was connected to the heat pipe. The capsule was broken under vacuum, and the entire assembly was heated to approximately 150°C for half an hour. The position of the entire assembly was such that any molten sodium would flow into the heat pipe. While the heat pipe was still connected to the exhaust pump, its temperature was raised to 425°C under vacuum, keeping the reservoir of sodium at 160°C. Pumping continued for a period of approximately 26 hours, at which time the copper manifold was pinched off from the heat pipe. The pinch-off of the niobium tube, part No. 12, was then accomplished by electron-beam melting of the tube.

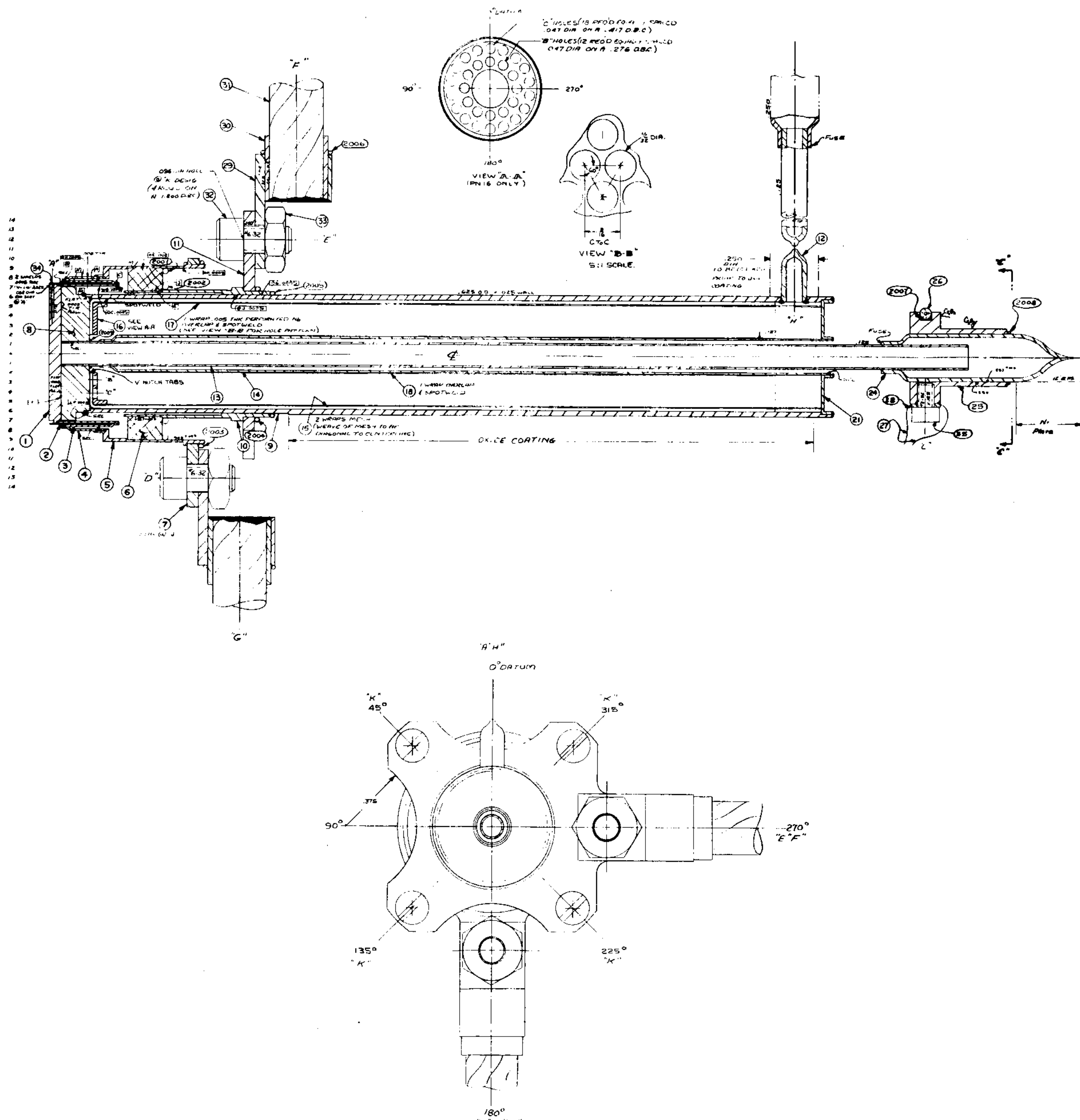
VIEW "A-A"
VIEW "B-B"
5:1 SCALE
OXIDE COATING
0° DATUM
45°
315°
90°
270°
135°
225°
180°

Figure 1

After completion of the electron-beam pinch-off operation, the copper tubulation simulating the cesium reservoir was fuse-brazed to the cesium tube. The tubulation was then pinched off and given a thin coating of black paint in order to help achieve low reservoir temperatures.

4. Test of Model T/E-1-D

Figure 2 shows the fully instrumented model T/E-1-D. Six thermocouples were placed along the radiating portion of the heat pipe at equal spacings, and a seventh thermocouple was placed on the cesium reservoir.

The thermal connection between the thermocouples and the wall on which they were attached was effected by means of ceramic cement, and to minimize the mechanical load on this junction, an additional wire support was wound around the insulated thermocouple leads as shown in the figure.

After the instrumentation was mounted on the heat pipe, the heat pipe was placed in a vacuum chamber in an upright position with the collector facing upwards, and an electron-bombardment unit was installed to heat the collector face. The data obtained at various heat inputs is shown in Table 1.

Data point No. 1 is the temperature distribution preceding test. Data point No. 2 shows the temperature distribution obtained with a nominal amount of filament heating and no electron-bombardment power applied to the heat pipe. Data points Nos. 3 to 8 give the temperature distributions obtained at various amounts of electron-bombardment power input. It can be seen that up to 311 watts of

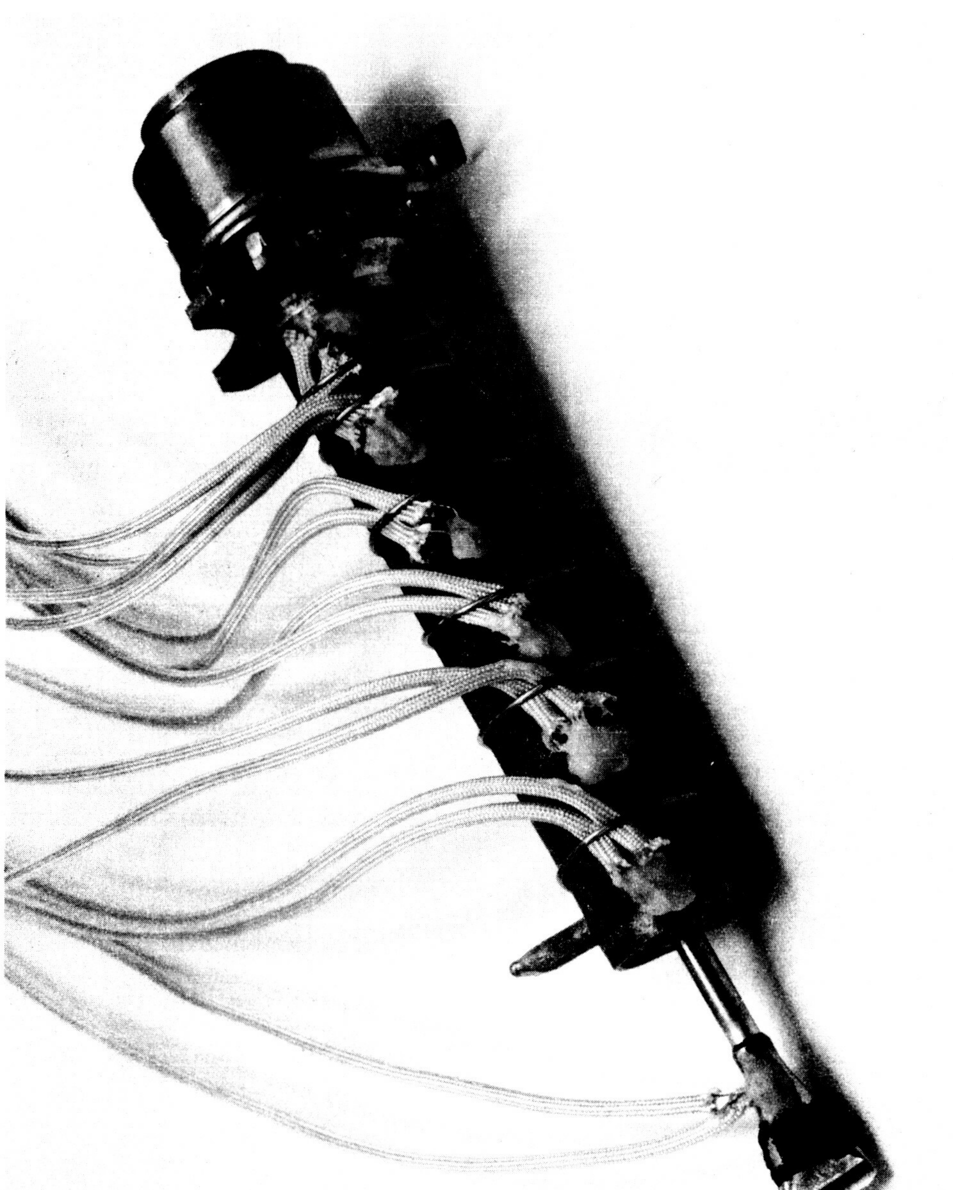

Figure 2

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TABLE 1

HEAT PIPE TEST DATA — DATE: 1-30-1967 — SHEET 1

OBSERVER: P. Brosem

MODEL: T/E-1D

	1	2	3	4	5	6	7	8	9	10	11	12
Time	10:20	13:07	13:45	15:15	15:45	16:07	16:22	16:37				
V_{eb}, volts	0	0	1027	1010	997	983	976	968				
I_{eb}, mA	0	0	43.6	76.1	121.4	191.5	251.7	321.4				
V_{Fil}, volts	0	4.4	4.4	4.6	4.8	5.1	5.2	5.4				
I_{Fil}, amps	0	20	20	20.8	21.7	22.6	23.0	23.6				
W_{Fil}, watts	0	88	88	95.6	104.1	115.2	119.5	127.5				
T.C.'s: Reservoir (14)	1.6	6.30	8.79	9.94	11.07	12.43	13.04	13.74				
°C	40	154	217	245	272	305	320	337				
HP #1 (top) (8)	1.6	11.75	19.07	22.44	25.84	29.65	31.90	33.86				
°C	40	289	463	542	622	712	766	814				
HP #2 mV (9)	1.6	10.50	18.36	21.84	24.97	28.44	29.82	30.60				
°C	40	258	446	528	601	681	716	735				
HP #3 mV (10)	1.6	9.90	18.30	21.67	24.90	28.62	30.29	31.71				
°C	40	244	445	524	600	687	728	761				
HP #4 mV (11)	1.6	7.60	14.65	17.35	20.15	23.78	25.66	27.62				
°C	40	187	358	423	488	574	617	664				
HP #5 mV (12)	1.6	7.12	14.18	16.85	19.61	22.83	24.69	27.41				
°C	40	175	347	410	476	552	595	659				
HP #6 (bottom) (13)	1.6	9.00	18.36	21.76	24.98	28.65	30.87	32.47				
°C	40	222	446	526	602	688	741	780				
Average of #1 & #6, °C	40	255	454	534	612	700	753	797				
W_{eb}, watts	0	0	44.7	76.8	121.1	188.3	245.4	310.6				
Pyrometer Reading, °C	(very high background reflections)							970				

electron-bombardment power input was applied, and heat pipe temperatures in excess of 800°C were obtained. The thermocouple locations on the heat pipe were numbered 1 to 6, starting from the top of the heat pipe.

Thermocouples 2, 3, 4 and 5 had a tendency to read substantially lower than thermocouples 1 and 6, at the top and bottom of the heat pipe. This was assumed to be due to a shorting of the leads of the low-reading thermocouples by the clamping wires shown in Figure 2. Later tests on Model T/E-2-C have shown that even the readings of the highest-output thermocouples are low because of thermal contact resistance between the heat pipe wall and the ceramic cement used for thermocouple bonding. For this reason, the temperature data given in Table 1 is discussed in Section 12 with that of Model T/E-2-C.

One particular observation which was made during the test of Model T/E-1-D turned out to have pivotal importance in the interpretation of the data collected on both models. This is the pyrometer reading which was taken during the test condition #8 in Table 1. It was taken next to the collector face in an attempt to determine the extent to which the collector temperature is the same as the heat pipe temperature, and, as will be shown in Section 12, only a very small difference occurs.

After completion of the thermal test shown in Table 1, the heat pipe was maintained at the maximum operating heat input of 335.4 watts overnight in order to accumulate an operating time of 100 hours at maximum power input, as specified in the Statement of Work. A thermal cycling test of 12 cycles would have followed the steady-state run of 100 hours. Sometime in the next 16 hours of running, however, the heat pipe developed a leak and lost the sodium charge.

5. Analysis of the Failure of Model T/E-1-D

Upon opening the test chamber to air, it became evident that the location of the sodium leak was near the weld between the sodium fill tube, part No. 12, and the heat pipe radiator tube, part No. 9. Figure 3 shows this area of the heat pipe, and the location of the leak can be identified by the white deposit of sodium hydroxide at the transition between the uncoated and coated portions of the heat pipe. The hydroxide is the result of the reaction of the residual sodium at the leak with the water vapor in the atmosphere.

The leak itself seemed to be in the form of a crack in an area where it appeared that a very narrow zone of the chromium oxide coating of the heat pipe had reacted with the heat pipe wall, presumably as a result of excessive heat during welding. To verify the fact that this weakening of the wall had occurred before exposure to sodium, another structure, which had been welded to serve as a back-up for T/E-1-D, was inspected. It is shown in Figure 4, and as can be seen, it did reveal the same characteristic reaction region at exactly the same location. Since this structure had not yet been filled with sodium, it was concluded that the reaction was caused by weld heat. Consequently, a new assembly was welded using copper chill blocks, and as shown in Figure 5, it was possible to obtain a very clean weld with no traces of any coating reaction.

6. Fabrication of T/E-2-A

Model T/E-2-A differed only in that the cesium reservoir was made of a chromium oxide-coated nickel piece on which thermocouples could be mechanically fastened, and Figure 6 shows a photograph of the unit fully instrumented. The instrumentation also differed in that

Figure 3

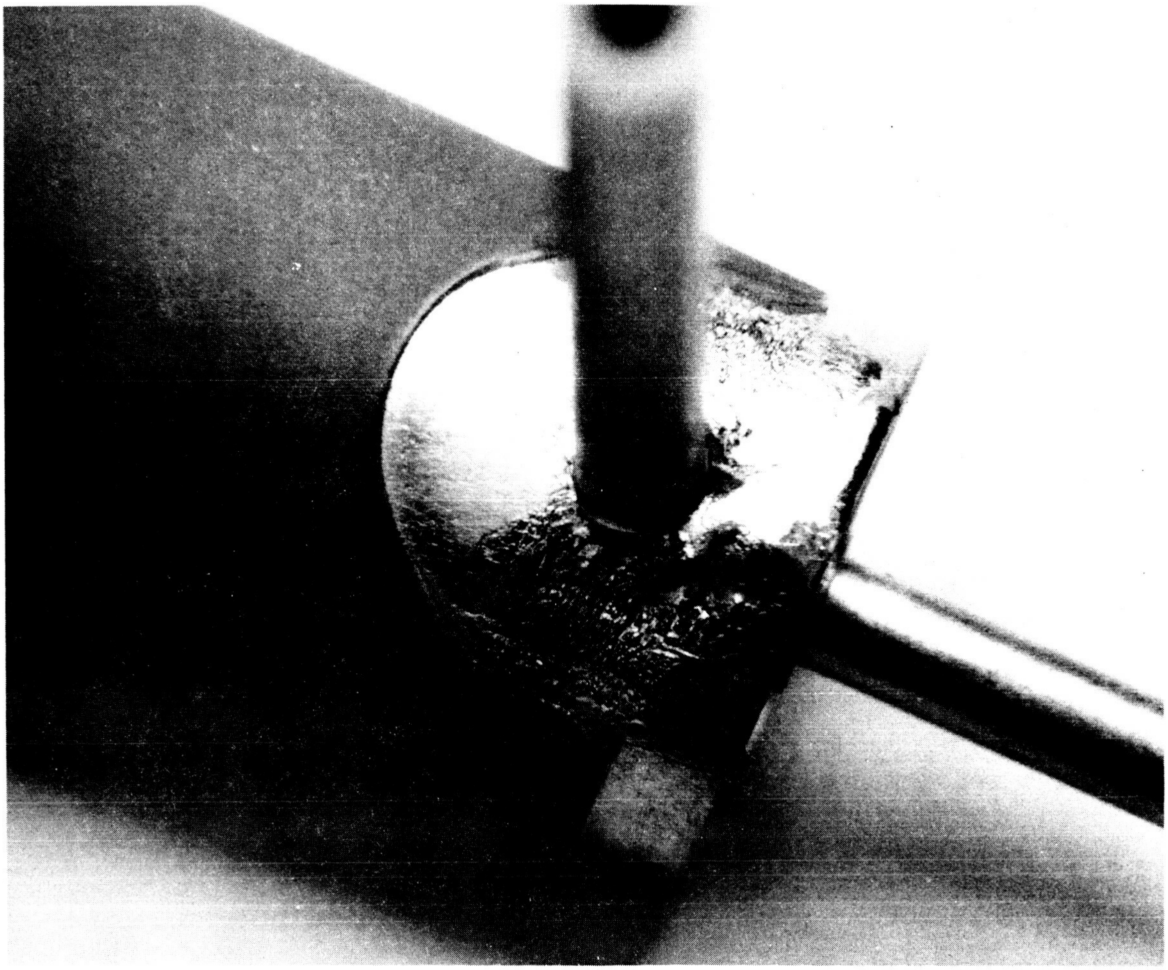

Figure 4

7556

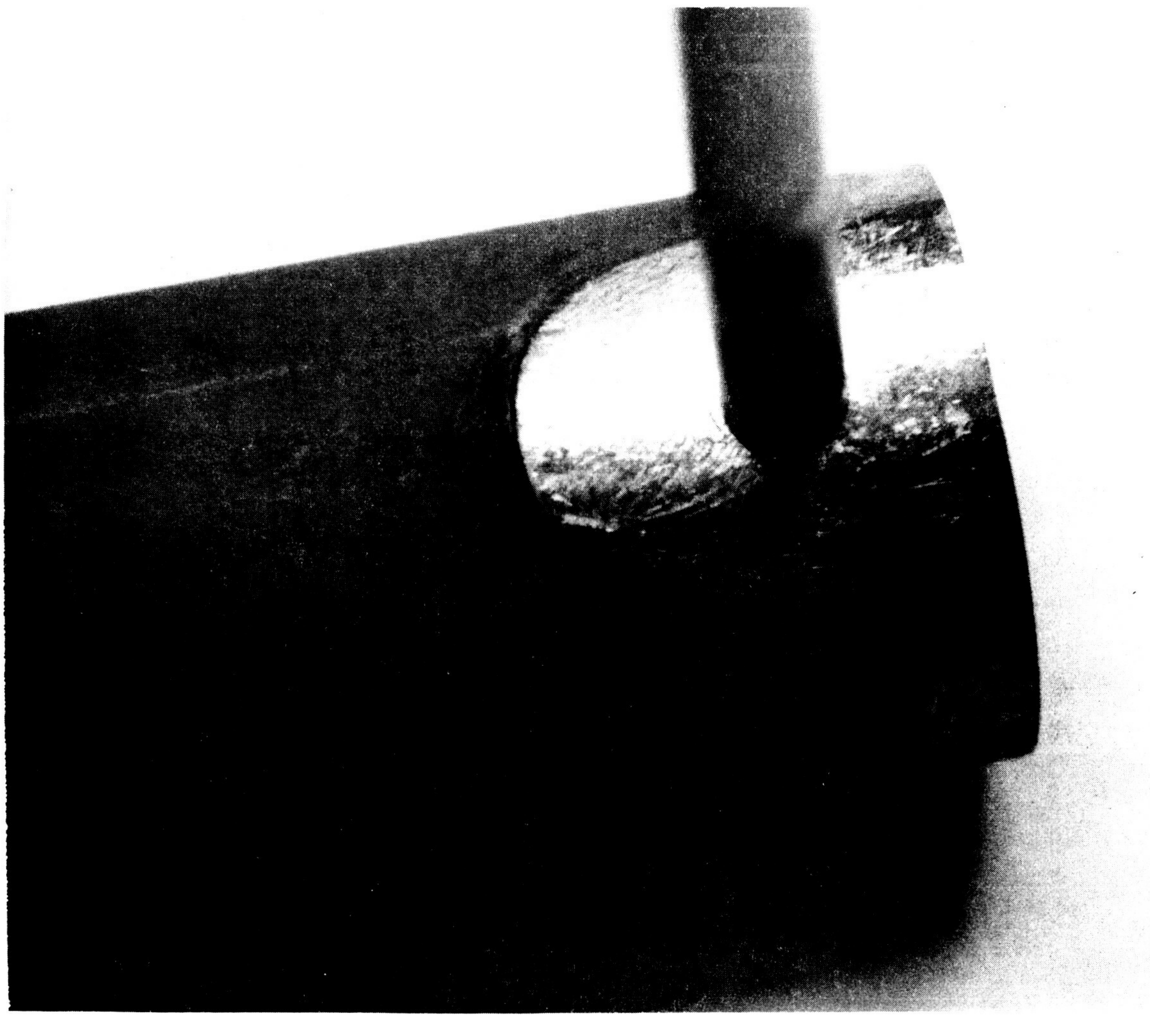

Figure 5

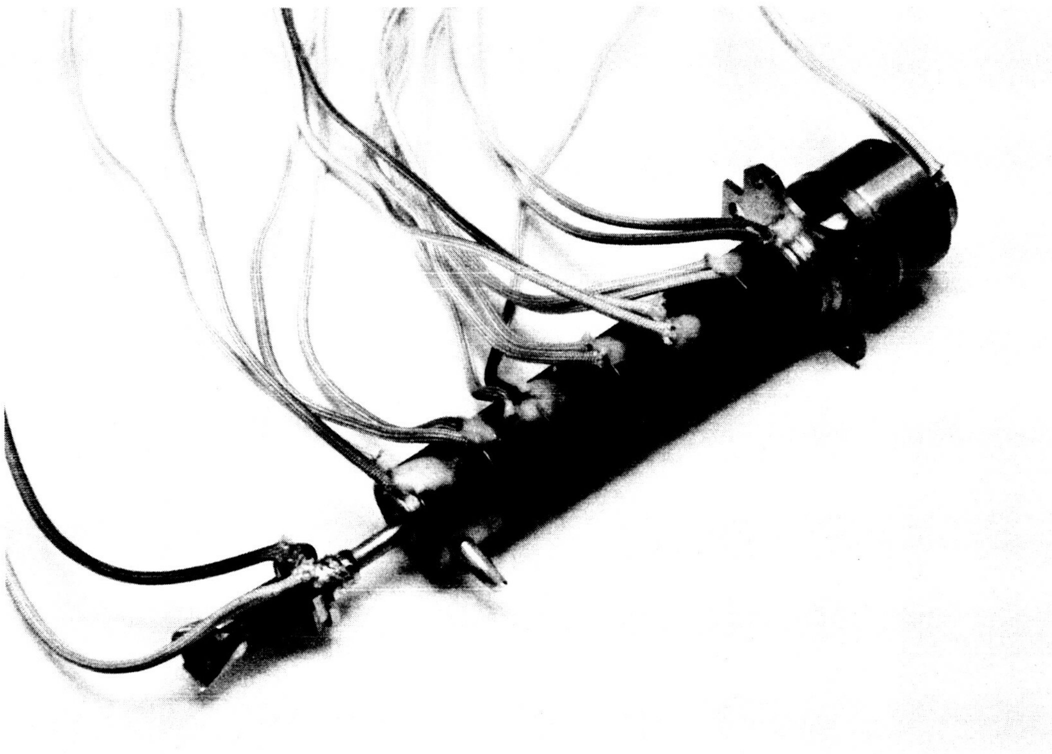

Figure 6

seven thermocouples were provided along the length of the heat pipe instead of six, and a thermocouple was attached to the collector face. The model was sodium-charged in the same manner as T/E-1-D except that the final niobium pinch-off was performed by electron bombardment rather than by electron-beam melting.

7. Testing of T/E-2-A

This model was set up for test, and the test data showed that no temperature uniformity could be achieved along the length of the heat pipe wall. This was an indication of either the presence of large amounts of gases or a lack of sodium within the heat pipe. The test was discontinued, and the heat pipe was opened by cutting its fill tube to examine whether any traces of sodium were visible. As none were seen, the model was placed in a vacuum furnace and heated at 900°C for two hours. A slight coating of sodium was produced over the surface of the vacuum bell jar in the first few minutes of heating. The amount so accumulated was so small that it was concluded that model T/E-2-A failed to operate because it lacked a sufficient charge of sodium to establish full wetting of the capillary conduit between the collector and the radiator surface. If full wetting is not obtained, the sodium can be expected to collect at the cool end of the heat pipe, and thus completely interrupt heat pipe operation.

Further examination of the tubulation from which sodium had been distilled into the heat pipe revealed that a large quantity of glass fragments had been produced upon breaking the capsule, and that many of the smaller pieces of glass had collected in the fill tube to the extent that this tube was almost completely plugged.

8. Fabrication of T/E-2-B

After T/E-2-A was vacuum-heated to remove its residue of sodium the niobium fill tube was cut, and a new tube was connected by means of an adapting piece made of niobium and brazed in place with palladium. The model was then outgassed and charged with sodium in the same manner as T/E-2-A except that care was taken to avoid breaking the sodium capsule at several places.

This model also failed to operate. It was opened by cutting the sodium fill tube, and it was placed in a vacuum furnace, where its temperature was raised to 1000°C. After 45 minutes of heating, no traces of sodium had been released, and it was concluded that the model did not contain any sodium. Inspection of the copper manifold used for sodium charging showed that the tube leading to the model had again become clogged by glass particles entrained by the sodium. This had occurred in spite of the effort made to avoid excessive crushing of the glass capsule, and it was concluded that, even when the glass capsules are cracked with the greatest care, they will still shatter into a large quantity of small fragments. Consequently, it was decided to incorporate a screen in the sodium fill manifold to retain the glass fragments.

9. Fabrication of T/E-2-C

When the next outgassing had been completed, a new sodium charging attempt was made, but this time it appeared that all of the sodium clung by capillary force to the sodium capsule, and again, none flowed into the heat pipe. The heat pipe model was reconnected to a new manifold, re-outgassed, and the sodium charge procedure was modified to drive the sodium out of its glass capsule and through the filter screen. Later examination of the manifold showed that practically all of the sodium had been driven into the heat pipe.

The weight of the completed heat pipe model T/E-2-C was 77.8 grams.

10. Test of T/E-2-C

Model T/E-2-C was instrumented in the same manner as T/E-2-A and tested at a range of power inputs to determine its ability to meet the design heat transfer conditions. Table 2 gives the observed temperature values. It is obvious that the collector face of this prototype, in contrast to that of model T/E-1-D, operated at a much higher temperature than the remainder of the heat pipe structure.

After measuring the response of the heat pipe to heat input, it was set for running continuously with the highest value of heat input at about 335 watts. At that time it was noted that, at the glowing edge of the collector, the temperature of the niobium tube welded to the collector would flicker at a high frequency in the region of the weld. This was certainly the result of intermittent capillary flow of liquid metal to the boundary between the cool wall and the hot collector, and the magnitude of the temperature excursions was approximately 50°C at a frequency of about 1 cycle per second. At the end of 23 hours of running in this condition, a sodium deposit was noticed on the bell jar, indicating a leak, and the test was terminated.

11. Analysis of the Failure of T/E-2-C

The model was first x-rayed to determine whether the installation of the capillary structure near the collector had been defective. This area cannot be inspected visually during assembly because then it lies at the bottom of a long cavity, and the visibility is further impaired by the presence of the collector insert, part No. 16, shown in Figure 1. In order to explain the operation of the collector at temperatures much higher than heat pipe temperature, it would be necessary to have either a loose assembly in which the capillary mesh screen was not in good contact with the collector, or the complete absence of the capillary mesh screen, as could occur if the screen slipped during insertion in the heat pipe. The x-ray obtained revealed a faint gap between the collector and the collector insert piece, which could be due to either one of the possibilities just mentioned: loose assembly or absence of capillary screen in that area.

The converter was then leak-checked, and the point at which the leak had occurred was found at the weld between the collector and the outer pipe.

After leak-checking, the converter was opened, and the collector end was potted and sectioned for metallographic examination. The heat pipe section collapsed during potting, but it was still evident that there was no capillary mesh screen between the collector and the collector insert piece. The elements of the other half of the potted structure were separated at the capillary screen boundary. There, the face of the collector insert piece was completely bare of capillary screen.

No unusual hardness was discovered over any part of the internal walls of the heat pipe, and therefore failure due to fracture at an embrittled area, such as occurred in T/E-1, is ruled out.

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TABLE 2

SHEET 1

HEAT PIPE TEST DATA

DATE: March 23, 1967

OBSERVER: P. Brosens

MODEL: T/E-2-C

	1	2	3	4	5	6	7	8	9	10	11	12
Date									3-23	3-24	3-24	3-24
Time	10:16	11:19	11:48	13:23	14:00	14:39	15:05	SAME CONDITION TEMPERATURES READ WITH PYRO.	18:05	10:35	14:31	16:35
Elapsed Time, hrs									SET ELAPSED TIMER AT 0 HAS 3.0 LETTING HEAT PIPE CONTINUE AT 321 mA INPUT	19.4	23.4	25.5
V_{eb}, volts	0	1023	1009	995	982	974	966			966	967	SODIUM DEPOSIT SEEN ON BELL JAR FACE LEAKING FROM COLLECTOR TEST TERMINATED.
I_{eb}, mA	0	43.9	76.9	123.1	191.9	251.1	321.0			321.3	321.7	
V_{Fil}, volts	4.9	4.2	4.5	4.7	4.9	5.0	5.2			5.1	5.0	
I_{Fil}, amps	21.0	18.8	19.9	20.3	21.1	21.8	22.1			21.7	21.6	
T.C.'s: Reservoir (14)	6.29	8.65	9.97	11.23	12.61	13.60	14.56	—		14.55	14.53	
°C	154	213	245	277	309	333	356			356	355	
HP #1 (top) (7)	12.96	18.50	21.88	25.08	28.83	31.42	33.68	822		33.46	33.43	
°C	318	450	529	604	693	754	810			804	803	
HP #2 (8)	12.18	18.62	21.99	25.18	28.87	31.40	33.64	822		33.39	33.33	
°C	299	452	532	607	693	754	808			802	801	
HP #3 (9)	11.42	18.69	22.13	25.36	29.17	31.72	34.02	822		33.84	33.82	
°C	280	454	535	611	701	762	817			813	812	
HP #4 (10)	10.76	18.76	22.12	25.36	29.19	31.73	34.03	922		33.89	33.86	
°C	265	456	535	611	702	762	8.8			815	814	
HP #5 (11)	10.20	18.63	22.03	25.27	29.08	31.61	33.88	822		33.67	33.64	
°C	251	453	533	608	699	759	814			809	808	
HP #6 ~~(bottom)~~ (12)	9.77	18.16	21.56	24.75	28.42	30.75	33.08	822		32.86	32.82	
°C	240	442	521	596	683	738	795			789	788	
HP #7 (bottom) (13)	9.58	17.77	21.35	24.75	28.32	30.68	32.82	818		32.78	32.73	
°C	235	432	517	596	680	737	788			788	787	
Collector (6)	17.14	24.34	29.57	34.34	38.85	41.6	48.5	—		45.4	45.2	
Pyrometer brightness °C	418	587	710	825 / 937	1036	1007 / 1074	1139 / 1163	—		980	979	

H.V. shut off at data pt #4 did not reveal stray emf on TC #6.

Pyrometer

From the above analyses it was concluded that the collector overheating was caused by imperfect assembly of the capillary mesh screen and the resulting absence of capillary connection of the collector. Furthermore, the leak is attributed to thermal fatigue of the collector weld, which was produced by the rapid temperature fluctuations in that area during heat pipe operation. With proper capillary assembly, both of these problems are avoided.

To investigate the difficulty of assembly of the capillary structure near the collector, a back-up assembly for T/E-2 was also x-rayed. It was seen that, in the collector area, the capillary structure did not reach the end of the heat pipe, and as a result, the collector insert piece was completely loose and had fallen off to one side.

To avoid these problems, future capillary structures will use a looser fit of the capillary structure into the heat pipe and greater use of pre-welded integral capillary structures, where slipping of the capillary screen cannot occur.

12. Analysis of T/E-1 and T/E-2 Performance

The heat pipe temperatures for T/E-1 and T/E-2 were very nearly the same at corresponding values of power input. An exact comparison is not made here because it is known that the thermocouples attached to the wall of the heat pipe do not remain well bonded and tend to read low. In order to ascertain the extent of this error, data point #7 for T/E-2 was read using the thermocouples, and data point #8 was taken under the same conditions, using the pyrometer to read heat pipe temperatures. It is seen that the thermocouples tend to show a heat pipe temperature of 810°C near the top, which decreases to 788°C near the bottom, while the observed pyrometer temperature was 822°C all along the wall except at the very bottom, where it was 818°C. Thus the temperature along the wall is much more uniform than the thermocouple readings indicate. Assuming a bell jar correction of 10°C and a pyrometer correction of 2°C, it is estimated that the true heat pipe temperature at a pyrometer reading of 822°C was 834°C, and therefore, the thermocouple with the highest reading was low by 24°C.

Figure 7 is a plot of the true collector temperature achieved in Model T/E-2-C, as measured by a spot-welded thermocouple, versus the pyrometer brightness temperature readings. With this curve, it is possible to estimate that the brightness temperature reading of 970°C performed on T/E-1-D corresponded to a true collector temperature of 841°C.

It is certain that T/E-1 achieved a slightly higher heat pipe temperature than T/E-2 at corresponding values of heat input because, with lower collector re-radiation, the heat load on the heat pipe was higher. Thus, at the conditions obtained with a bombardment current of 321 mA, it is reasonable to assume that the heat pipe temperature of T/E-1 was higher than 834°C, and therefore the temperature drop between the collector, which was estimated to be at 841°C, and the heat pipe must have been less than 10°C.

The most important result of the heat pipe tests is the relationship between collector heat transfer and collector temperature. To obtain this relationship, the T/E-1 data was used in spite of the fact that this model was not so well instrumented as T/E-2. The choice was made because T/E-1 achieved correct heat pipe operation, and the collector overheating of T/E-2 disturbs the heat transfer conditions to an extent that cannot be calculated accurately.

The collector temperatures of T/E-1 were obtained assuming the 841°C estimated value for data point #8, which is 27°C higher than the highest thermocouple reading, and arbitrarily scaling down the 27°C temperature correction for the data points at lower heat transfer values.

The heat transfer values were obtained by adding the filament heating to the electron-bombardment power input, and the filament heating was calculated by an analysis of the heat pipe temperature achieved with filament heating alone. Specifically, Data points 2 and 3 of Table 1, where the filament power is the same but where the temperature distributions are different on account of the additional electron-bombardment power of data point 3, were compared in terms of a simple heat transfer balance to determine the magnitude of the filament heating effect. The result of this calculation is that the filament heat input for data points 2 and 3 is 17.1 watts. Assuming that the filament power input to the heat pipe is proportional to the power actually delivered to the filament, as measured by filament voltage and filament current, the filament power input for the other data points can be calculated.

Table 3 gives a summary of the calculations, and the resulting values of collector temperature and collector heat transfer are plotted in Figure 8.

Since, according to Monthly Report No. 13 of JPL Contract 951263, the collector heat transfer is related to converter output current at 1700°C by the relation:

$$Q_{collector} = 105.7 + 1.92\, I_o \qquad (1)$$

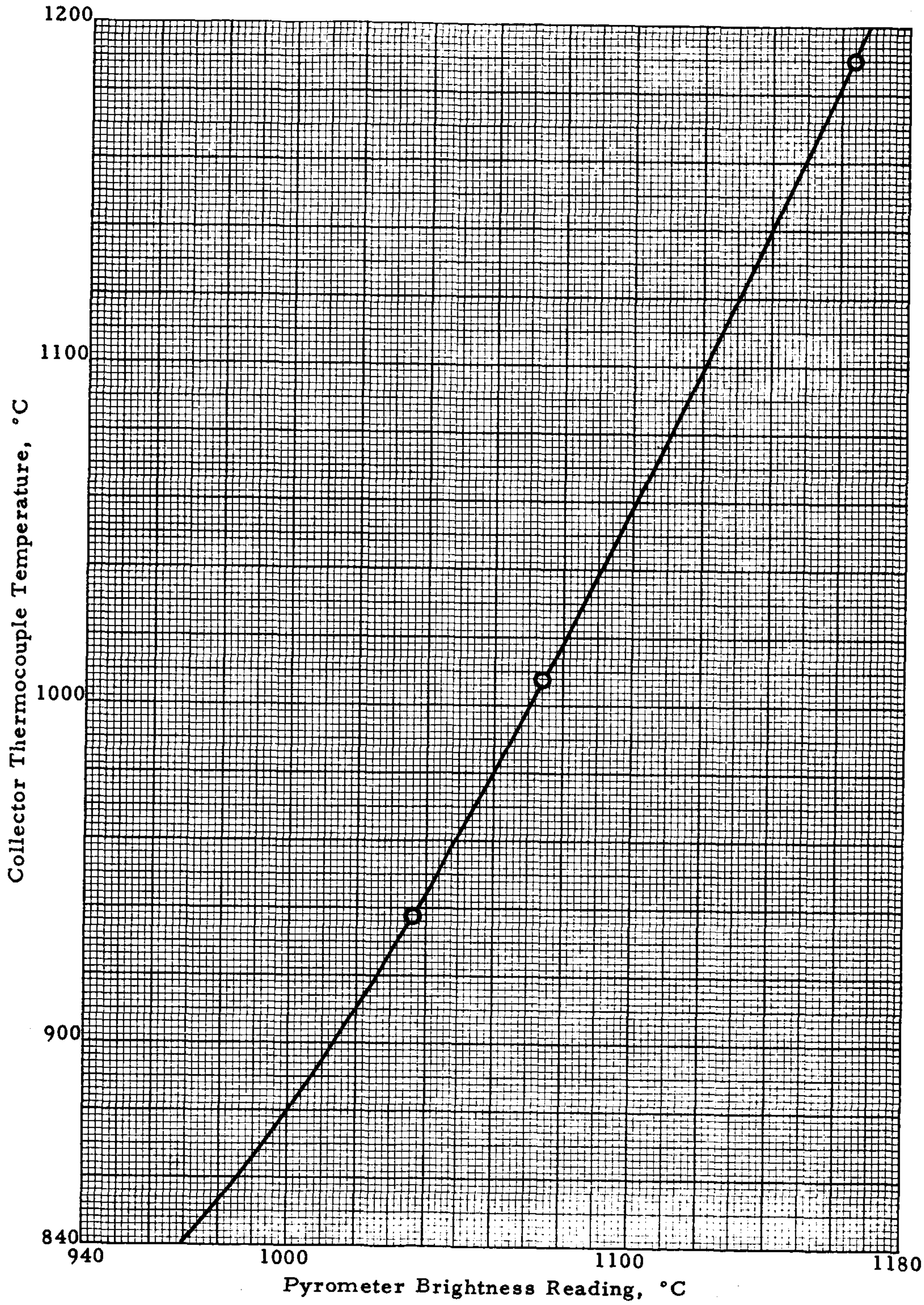
1200
1100
1000
900
840
940
1000
1100
1180
Collector Thermocouple Temperature, °C
Pyrometer Brightness Reading, °C

Figure 7

TABLE 3

SUMMARY OF HEAT PIPE CALCULATIONS

Data Point	Highest Thermocouple Reading, °C	Estimated Temperature Difference, °C	Collector Temperature, °K	Calculated Filament Power, W	Electron-Bomb. Power, watts	Total Power Input, watts
3	463	17	753	17.1	44.7	61.8
4	542	19	834	18.6	76.8	95.4
5	622	21	916	20.2	121.1	141.3
6	712	23	1008	22.4	188.3	210.7
7	766	25	1064	23.2	244.4	267.6
8	814	27	1114	24.8	310.6	335.4

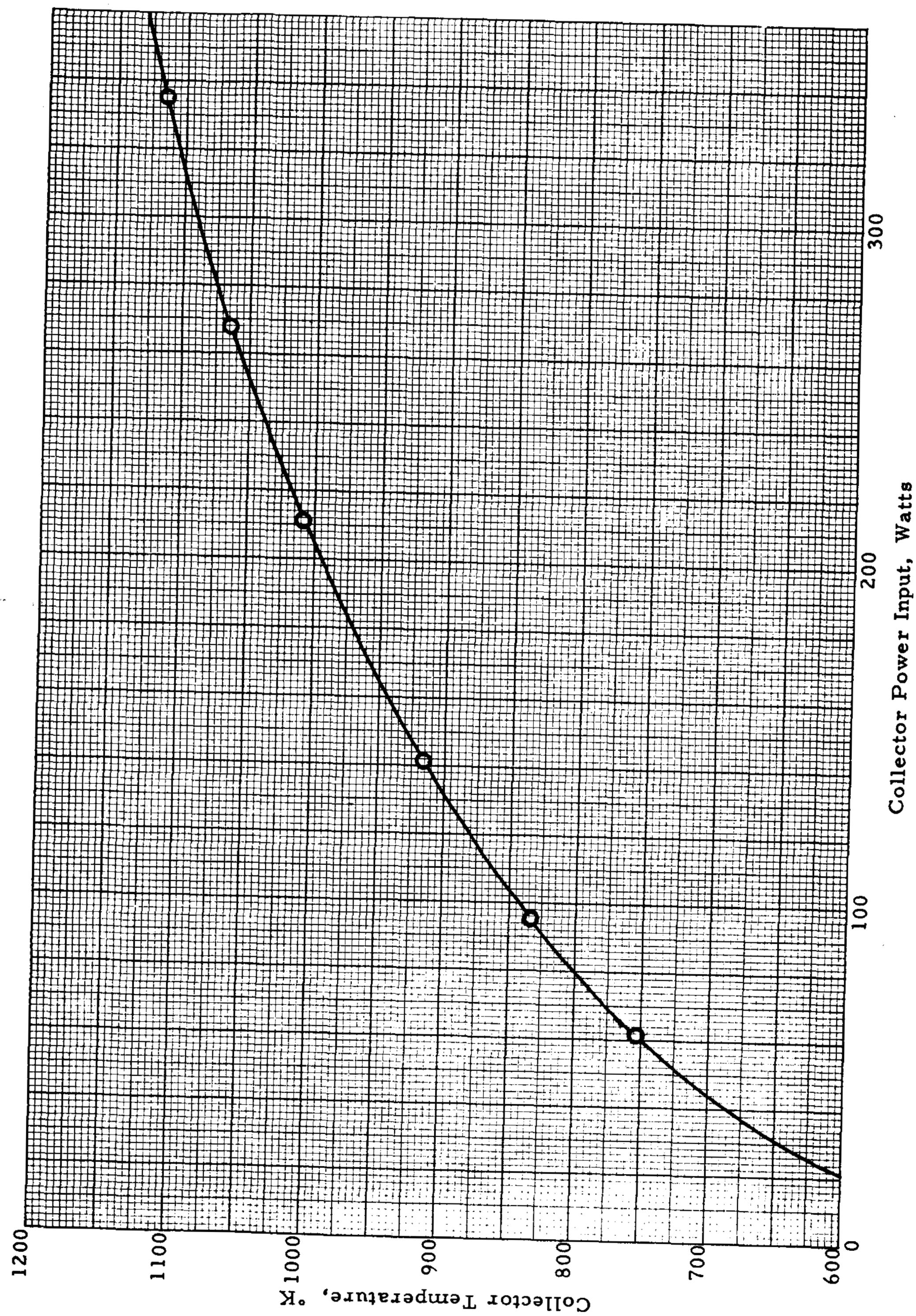
Collector Power Input, Watts
0
100
200
300
Collector Temperature, °K
1200
1100
1000
900
800
700
600

Figure 8

Figure 8 can be used to predict the collector temperatures that will be achieved in a heat pipe converter as a function of output current at 1700°C. The predicted curve is given in Figure 9, which also shows the pertinent data on converter T-206, developed under JPL Contract 951263, to show that the heat pipe will considerably improve the collector heat transfer of the T-200 converter.

Finally, Table 2 shows that, in spite of the overheating of the collector and the consequent greater transfer of heat to the cesium reservoir, the reservoir temperatures are well within the range of control required by the design. For instance, at the design value of output current of 51 amperes, the optimum reservoir temperature is above 621°K (Data point 5, Sheet 4, T-206 data). According to Equation 1, the heat transfer corresponding to an output of 51 amperes is 203.7 watts. It can be seen in Table 2 that, at near this value of heat input, the reservoir temperature obtained in T/E-2 is of the order of 309°C, or 582°K, which is almost 40°C below the desired value, and therefore reservoir overheating is easily avoided by the T/E-2 design.

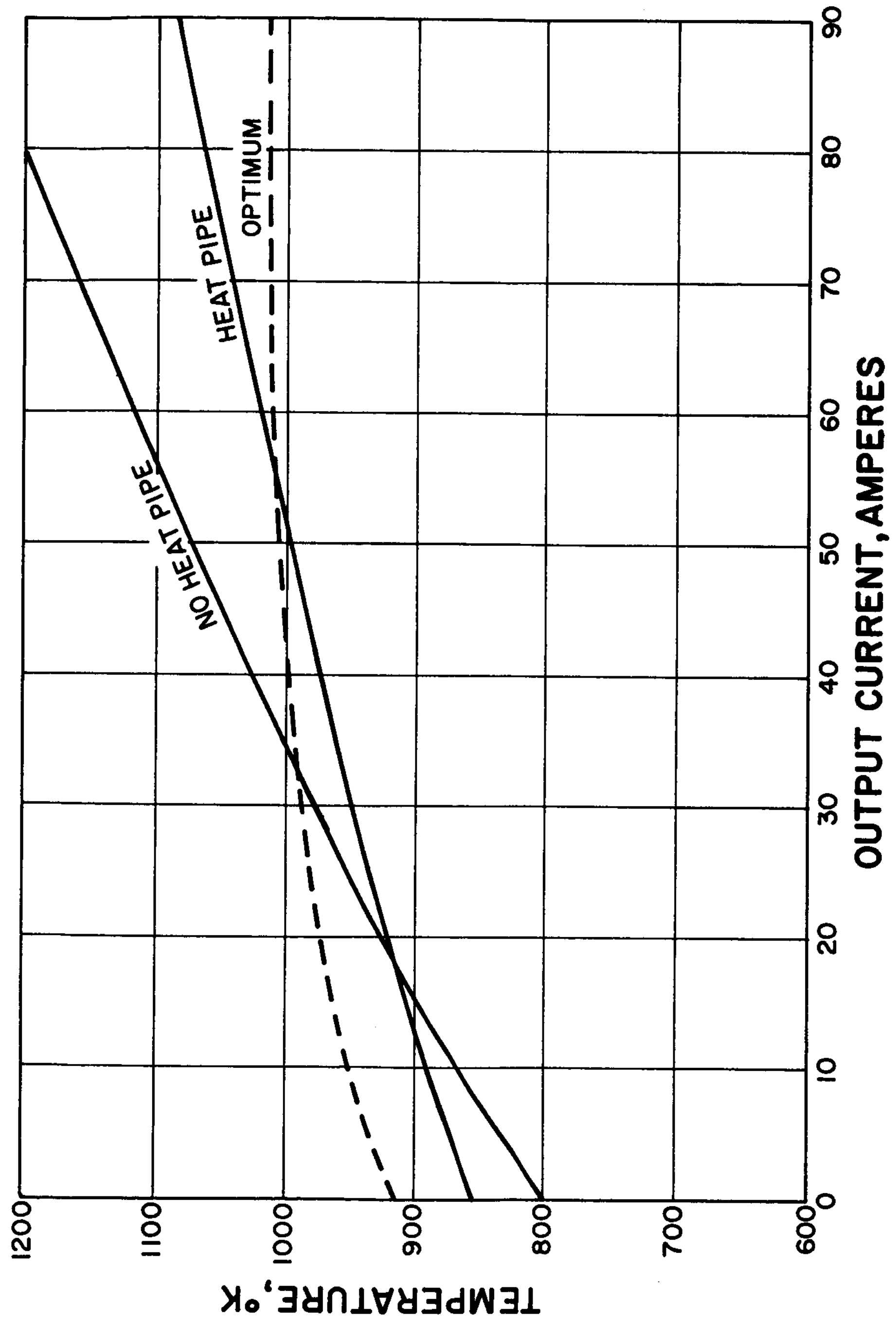
TEMPERATURE, °K
1200
1100
1000
900
800
700
600
OUTPUT CURRENT, AMPERES
0
10
20
30
40
50
60
70
80
90
NO HEAT PIPE
HEAT PIPE
OPTIMUM

Figure 9